International Journal of Progressive Sciences and Technologies (IJPSAT)
ISSN: 2509-0119.

Vol. 45 No. 1 June 2024, pp. 480-497

Coal Supplier Selection for Energy Management Optimization: Case Study in a Coal-Fired Power Plant using integrated Analytical Hierarcy Process and Monte Carlo Simulation

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Abstract— Coal supply management decision, especially in supplier selection and receiving strategy, plays a crucial role in the efficiency and resilience of primary energy source for a coal-fired power plant (PLTU). Suppliers' commitment, logistic disruptions, and other risks present uncertainty in the decision-making process. This research proposes a multi-criteria decision-making (MCDM) model methodology with an integrated Analytical Hierarchy Process and Monte Carlo simulation (AHP-MC) approach for coal suppliers' selection and receiving strategy optimization that considers uncertainty in the energy planning development for PLTU Pelabuhan Ratu, West Jawa - Indonesia. The AHP model analysis aims to determine the optimal coal supplier selection based on criteria such as price, coal quality, supply delivery reliability, and coal receiving strategy through order management and forward contracts. The Monte Carlo simulation method is used as a simulation for criteria laden with uncertainty in the coal supply chain, such as coal quantity and quality to coal reserve stocks. The instrumentation analysis uses Expert Choice 11 software for AHP modeling of coal supplier selection, and Microsoft Excel with add-ins Crystal Ball for Monte Carlo simulation and Log-Hub for routine demand forecasting simulation based on historical data of coal supply chain management at PLTU Pelabuhan Ratu. The result shows that the coal demand data trend is distributed in minimum extreme pattern. The optimum point of demand is expected by 338.6 thousand ton which lead the productivity of electricity generation about 72,52% of its maximum capacity. The demand of coal is highly recommended to be supplied by 9 top priority of the chosen suppliers based on AHP model. The model proposed is potentially 4.40% more efficient than current ongoing coal demand in term of sustainability of electricity supply management. The output and contribution of this research are expected to be input as an alternative model for coal supply management decision optimization, increasing production system development in the energy sector and energy efficiency at PLTU Pelabuhan Ratu.

Keywords—coal supply, energy management, AHP, supplier selection, coal-fired power plant

I. INTRODUCTION

Coal remains the dominant energy source in Indonesia, accounting for 66% of the national energy mix in 2021 [1]. The demand for domestic coal consumption is exhibiting a positive growth trend, averaging around 7.48% annually [2], surpassing the global forecast of 5% by the International Energy Agency [3]. Notably, the highest growth rate was recorded in 2022 at 32%, attributed to the post-pandemic economic recovery and domestic industrial development [4].

According to local regulation in West Java [5] on the Regional Energy Master Plan for West Java Province 2018-2050, coal usage as a fuel for power plants and industries like textiles and cement accounts for 98.78% of the region's primary energy mix, contributing to a total of 24.53%. Energy demand projections indicate that coal requirements for power plants in West Java will increase by 8.71% annually until 2050, reaching 69.4 million tons, representing 29.46% of the energy mix. This local coal demand growth trend surpasses the national increase of 7.8% and the average annual coal production growth rate of 7.18% until 2023 [6]. This unbalanced growth pattern necessitates optimizing coal supply management and energy management to ensure supply stability and power plant operational sustainability.

Reference [7] revealed that economic growth, energy prices, and technological innovation positively impact coal consumption in Indonesia between 2000 and 2018. However, this increased coal usage does not necessarily translate into improved profitability for companies or enhanced supply chain management capabilities [8]. Therefore, to ensure a stable coal supply, power plant operators must also optimize their supplier relationships. While these suppliers may not exhibit strong profitability, their operational efficiency remains crucial for maintaining the coal-fired power plant operations.

Optimizing coal supply in a coal-fired power plant is crucial to ensure energy production stability, prevent supply deficits, and minimize costs. This optimization involves two key aspects; selecting reliable coal suppliers and implementing efficient coal receiving processes. Choosing dependable coal suppliers is essential for maintaining a stable supply and reducing logistics expenses [9]. Reliable suppliers can consistently deliver high-quality coal at agreed-upon quantities and prices, minimizing disruptions to the power plant operations. While, streamlining coal receiving processes plays a vital role in lowering exergy losses and saving overall costs [10]. Efficient processes minimize delays, optimize handling, and ensure accurate coal quality assessment, contributing to overall plant efficiency.

This research aims to investigate the influence of supplier selection and coal receiving efficiency on coal supply availability and electricity production at Pelabuhan Ratu coal-fired power plant, a medium-scale power plant (3x350 MW) located in southern West Java, Indonesia. The supplier selection process will employ the analytical hierarchy process (AHP) model, a widely used tool in management for decision-making and analysis [11]. The AHP model will incorporate crucial factors in supply and energy management, including coal quality and price, supplier reliability, supply sustainability, supply receiving strategies and supplier contracts. The coal receiving efficiency study will utilize Monte Carlo simulations to assess the variability in coal demand at the power plant and the realization of supply from each supplier.

The outcomes of this research are expected to have a positive and significant impact on various aspects of coal supply and electricity production at Pelabuhan Ratu coal-fired power plant and provide valuable insights for optimizing energy management practices. By understanding the relationship between coal supply availability and electricity production capacity, the research can inform strategies for maximizing power plant output. This could involve selecting suppliers based on their ability to meet demand fluctuations and optimizing coal receiving processes to minimize logistics and electricity production costs.

II. Literature Review And Methodology

2.1. Coal-fired Power Plants and Energy Management Challenges in Indonesia

Coal-fired power plants (CFPPs), like the Pelabuhan Ratu Power Plant (PLTU Pelabuhan Ratu) in Indonesia, remain a significant source of electricity generation. However, their reliance on coal presents challenges for efficient energy management. Optimizing coal selection is crucial for minimizing costs, maximizing plant performance, and ensuring a reliable electricity supply in Indonesia.

Fuel supply optimization is a crucial aspect of energy management. In a coal-fired power plant, by strategically blending, and managing coal, energy management focuses on optimizing operations to generate electricity more efficiently and reliably. Diversifying fuel sources and suppliers creates a more secure energy supply [12], reduces the risk of shortages [13], and improves power plant capacity management for extreme demand periods [14]. Despite not demonstrating strong profitability, the power plant's operations remain stable [15[. To maintain a stable and controlled energy production within a limited range, continuous monitoring is essential to ensure the supplier's commitment to delivering high-quality energy sources. This continuous monitoring must be balanced dynamically with efforts to manage cost aspects [16].

Selecting the right coal suppliers is crucial for a coal-fired power plant as it directly impacts their operation and efficiency. Reliable suppliers ensure consistent delivery of high-quality coal at competitive prices, minimizing disruptions, optimizing logistics, and controlling costs [17]. An effective supplier selection model further reduces supply uncertainty, enhances operational stability, and contributes to a more secure and affordable electricity supply for the region [9]. Research demonstrates the effectiveness of MCDM techniques like the Analytical Hierarchy Process (AHP) in evaluating and ranking coal suppliers based on multiple criteria and decision-maker preferences, applicable to the PLTU Pelabuhan Ratu [18].

In energy sector, the criteria of suppliers' selection are comprised by the supply side capability, i.e., fuel price, quality, delivery time, technical ability [19], flexibility and response [20], and stock capacity [21]; and demand side receiving mindset to seek optimal order allocation [22,23,24], sustainability in energy supply chain management [25], and optimal supply contract [26,27] in which those options rely on the minimum realization of allocation contract and logistic costing. The integration of both side criteria is expected to be more reliable consideration to determine more accurate minimum realization [27] for energy generation and logistic cost efficiency [28].

A significant portion of research publications on logistics optimization within energy supply chain management employ deterministic models [9]. Deterministic methods are mathematical models where parameters can be measured with a high degree of certainty. This allows for optimization based on average coal supply and logistic cost values. In contrast to logistics optimization, energy supply chain management often necessitates a stochastic approach that incorporates randomness and uncertainty into its models as what become the background of the previous references [22-27]. This is due to the inherent variability in energy production data, which is influenced by factors such as losses and disruptions in the dynamic energy system [28]. Studies highlight the inherent variability in energy demand, influenced by factors like weather patterns and economic activity. Monte Carlo Simulation (MCS) is recognized as a valuable tool for predicting future demand and assessing its impact on decision-making at the PLTU Pelabuhan Ratu [29, 30].

The proposed research aims to bridge the gap between deterministic and stochastic approaches in energy supply chain management by incorporating stochastic elements (demand assumption) into the optimization model. This approach addresses the inherent uncertainty in energy supply chains, particularly in terms of delivery times and the quality of delivered coal. This enables the model to capture the complexities of energy supply chains while providing a robust solution that can handle uncertainty.

2.2. Gaps in Existing Research

While existing research offers valuable insights into coal supplier selection and energy management in coal-fired powerplants, a gap exists in integrating these aspects into a comprehensive framework specifically applicable to the Indonesian context.

- Limited role of MCS for Indonesian CFPPs: Current research often employs MCS for a broader range of uncertainties. In this study, the focus of MCS will be solely on predicting future coal demand for the PLTU Pelabuhan Ratu.
- Addressing Uncertainty and Supplier Selection for PLTU Pelabuhan Ratu: Research can be further developed by utilizing predicted demand from MCS to guide supplier selection through AHP, considering Indonesian regulations and specific needs of the PLTU Pelabuhan Ratu.

2.3. This Research Contribution

This research addresses the identified gap by proposing an integrated methodology that combines:

- AHP: To prioritize criteria for coal supplier selection based on expert judgment, strategic objectives, and Indonesian regulations, specifically tailored to the PLTU Pelabuhan Ratu.
- Prediction of Coal Demand Using MCS for PLTU Pelabuhan Ratu: To assess the variability and potential range of future coal demand at the PLTU Pelabuhan Ratu.

This integrated approach aims to provide a more robust decision-making framework for selecting optimal coal suppliers that can meet the predicted coal demand for the PLTU Pelabuhan Ratu while considering other critical factors, all within the context of Indonesian regulations and the specific needs of the power plant.

III. METHODOLOGY

This section details the methodological approach employed in this study to select optimal coal suppliers for energy management optimization at the Pelabuhan Ratu Power Plant (PLTU Pelabuhan Ratu) in Indonesia. The methodology integrates two key techniques:

1. Analytical Hierarchy Process (AHP): This multi-criteria decision-making (MCDM) approach structures the selection process by considering various criteria and alternatives (coal suppliers) based on their relative importance and performance, tailored to the PLTU Pelabuhan Ratu and Indonesian regulations.
2. Monte Carlo Simulation (MCS): This computational method simulates random variations in historical coal demand data specific to the PLTU Pelabuhan Ratu to predict a range of possible future demand values.

The following sections detail the implementation of each technique within the overall methodology framework. Here, the predicted coal demand from MCS will be used to inform the selection of coal suppliers through AHP, considering the specific context of the PLTU Pelabuhan Ratu.

3.1. Analytical Hierarchy Process (AHP)

According to [31], the Analytical Hierarchy Process (AHP) is a structured decision-making approach in the field of management that analyzes comparisons between various criteria and alternatives to determine the most optimal choice. It is a multi-criteria decision-making (MCDM) method that allows for the systematic evaluation of complex problems involving multiple factors and objectives. There are 4 key features of AHP: i) Hierarchical Structure: The AHP breaks down a decision problem into a hierarchy, consisting of a goal at the top, followed by levels of criteria and sub-criteria, and finally, alternatives at the lowest level; ii) Pairwise Comparisons: The AHP utilizes pairwise comparisons to assess the relative importance of criteria and the relative preference of alternatives against each criterion. These comparisons are made on a scale of 1 to 9, representing equal importance or preference to extremely strong importance or preference. iii) Consistency Checks: The AHP incorporates consistency checks to ensure that the pairwise comparisons are logical and consistent. This helps to avoid biased or inaccurate judgments. iv) Synthesis of Priorities: The AHP synthesizes the pairwise comparisons into numerical weights for each criterion and alternative. These weights represent their relative importance or preference in the overall decision-making process.

In this study, there are 18 alternative suppliers examined in the AHP modelling. To determine the suppliers priority rank based on AHP method, the criteria of supplier selection are decomposed into six main factors and 16 parameters: (1) quality which is consisted of caloric value, total moisture, total Sulphur, and ash content, (2) price, (3) supplier reliability which is consisted of percentage of supply realization, delivery time, and response, (4) supply sustainability which is consisted by coal mine stock and stockout risk, (5) ordering strategy which is decomposed into just in time, fixed order quantity, economic order quantity, and safety stock, and (6) contract strategy which is consisted of short-term contract, mid-term contract, and long-term contract. 2 experts from PLTU Pelabuhan Ratu planning department become respondents in which their judgement used as bases of criteria and supplier priorities. AHP calculations are performed by Expert Choice 11 software.

3.2. Monte Carlo Simulation (MCS)

Monthly coal supply data covering the period 2020-2023 are utilized in this study as received amount based. Crystal Ball software is utilized to determine the best probability distribution, run the Monte Carlo simulation and predict the demand assumption. Number of trials used in this study is set in 10,000 times iteration. Coal quality data, such as caloric value and heat rate are obtained from shipment and production report in internal department of PLTU Pelabuhan Ratu. Whole data are analyzed using Crystal Ball software to get the result its statistic. The likeliest or mean values of supplied coal will be used as the standard of operational value calculation in the I/O analysis.

3.3. Input-Output (I/O) Energy Conversion Analysis

The I/O energy conversion analysis will evaluate the potential impact of different coal types on the PLTU Pelabuhan Ratu's efficiency. This analysis will help identify the best scenario of coal supplier that fit the number of predicted demands, optimize plant performance and minimize fuel cost.

1) The practical equation of I/O energy conversion used in analysis is [32]:

$$\boldsymbol{Electricity\ production}\ (kWh/month) = \Sigma\ (Caloric\ Values \times Allocations)\ /\ heat\ rate; \tag{1}$$

in which heat rate value is assumed applicable to all operational condition. This approach assumes a relatively consistent boiler design and operational practices at the PLTU Pelabuhan Ratu, minimizing the impact of factors beyond coal quality.

2) From electricity production, the value is divided by number of hours monthly to seek for energy generation per hour. Assumes that average month has 30.5 days. So, the equation of energy generation every hour will follow the formula:

$$\boldsymbol{Electricity\ production}\ (kW) = Electricity\ produced\ (kWh/month)\ /\ (24x30.5); \quad (2)$$

3) The plant capacity is calculated using the formula:

$$\boldsymbol{Capacity\ Factor} = Electricity\ produced\ (kW)\ /\ (3x350{,}000\ kW); \quad (3)$$

4) Logistic cost (in rupiah/kg) is calculated using formula:

$$\boldsymbol{Logistic\ cost} = sum\ product\ of\ CIF\ /\ \Sigma\ Allocations; \quad (4)$$

5) While proportional cost to productivity cost is calculated using formula:

$$\boldsymbol{Operational\ cost} = sum\ product\ of\ CIF\ /\ Electricity\ production\ (kWh); \quad (5)$$

3.4. Scenario Planning

To achieve the goal of optimal energy production and stable supply to the power plant, based on the available information need some constraint assumptions:

- Set the minimum demand of supply (based on mean value of distributed data statistic) as the supply target to fulfill monthly.
- Heat rate value is set in advance. The number represents average measured heat rate values in the system. Thus, the boiler system is assumed to be identical for all scenarios.
- Caloric value used in calculations is gross caloric value as received based in the power plant. Mean caloric values of each suppliers are used as the reference of supply realization qualities.
- The final expected result in the I/O calculations is estimated electricity production from several planed scenarios.

Based on the assumptions, there are six scenarios planning arranged:

1) The coal demand is in its minimum point.
2) The coal demand is higher than its minimum point, close to maximum estimated value by routine simulation (here, we use Log-Hub application to run the simulation). The supply allocation will be shared proportionally as the suppliers list from AHP.
3) The coal demand is higher than its minimum point, close to maximum value of demand historical data in 2020-2023. The supply allocation will be shared proportionally as the suppliers list from AHP. The suppliers' allocation based on the mean value of their supply statistic.
4) The condition is similar to scenario 2, but the allocation share is only for top 9 suppliers on the AHP priority supplier list.
5) The condition is similar to scenario 3, but the allocation share is only for top 9 suppliers on the AHP priority supplier list.
6) The coal demand is according to average value of routine simulation, without through the MCS analysis to determine the demand mean/likeliest value (no prior optimization of the demand probability). The supply allocation will be shared proportionally as the suppliers list from AHP.

IV. Results and Discussion

4.1. AHP Results and Supplier Ranking

Table IV.1 shows the result of analytical hierarchy process (AHP) calculation with their assigned weights based on expert judgment. The result outlines the key factors and sub-factors considered when selecting coal suppliers for the Pelabuhan Ratu

Power Plant (PLTU Pelabuhan Ratu) in Indonesia. This analysis dissects the information to understand the priorities and considerations for optimal coal supplier selection.

There are 6 main criteria and 16 factors have been examined using pairwise comparison matrix method. Two experts participate in the research. The similarity between the combined result and some individual expert judgments suggests a degree of consensus on the overall priorities. Discrepancies between experts highlight areas for different sense of urgency. Some discussions between experts have been facilitated to refine the weightage and ensure all perspectives are considered. The inconsistency ratios indicate that all expert's judgement (8% and 0%) and their agreement (2%) are at good level of consistency.

Based on expert 1 judgment and AHP analysis, we can see that Supply Sustainability (52.3%) is the most critical factor, followed by Supplier Reliability (11.9%). While, expert 2 gives more concern about the quality of supply (48.5%) followed by Supplier Reliability (20%). Expert 1 appears to prioritize Supply Sustainability to a similar degree as the combined result. However, their weightage distribution within this category might differ. Expert 1 might assign a higher weight to Coal Stock (within Supply Sustainability) compared to Expert 2, given the overall importance of this sub-criterion. Expert 1 might place slightly less emphasis on Quality and Supplier Reliability sub-criteria compared to the combined result. Expert 2 might prioritize Supplier Reliability more than Expert 1, potentially assigning higher weights to sub-criteria like Supply Realization and Delivery Time. Besides, Expert 2 might show a slight inclination towards considering Price or short-term contract options within Contract Strategy compared to Expert 1.

TABLE **ERREUR ! IL N'Y A PAS DE TEXTE REPONDANT A CE STYLE DANS CE DOCUMENT.**.1 CRITERIA WEIGHT ON SUPPLIER SELECTION MODEL RESULT USING ANALYTICAL HIERARCHY PROCESS (AHP)

Criteria	**Sub-criteria/ Factors**	**Priorities**		
		Expert 1	***Expert 2***	***Combined***
Quality		5.1%	48.5%	19.7%
	Caloric value	2.0%	29.7%	10.0%
	Total Moisture	2.0%	13.5%	6.8%
	Total sulphur	0.7%	3.3%	2.0%
	Ash content	0.3%	2.1%	1.0%
Price		2.5%	3.0%	3.5%
Suppliers reliability		11.9%	20.8%	20.0%
	Supply realization	5.4%	16.3%	12.8%
	Delivery time	5.4%	2.8%	5.3%
	Response	1.1%	1.7%	1.8%
Supply sustainability		52.3%	10.5%	29.5%
	Coal stock	45.8%	9.2%	25.8%
	Stockout risk	6.5%	1.3%	3.7%
Ordering strategy		9.9%	2.7%	6.6%
	Just in time	3.8%	0.4%	1.8%

Criteria	Sub-criteria/ Factors	Priorities		
		Expert 1	*Expert 2*	*Combined*
	Fixed order quantity	1.0%	0.1%	0.5%
	Economic order quantity	3.3%	0.4%	1.7%
	Safety stock	1.8%	1.7%	2.6%
Contract strategy		18.2%	14.5%	20.7%
	Short-term contract	1.2%	10.3%	6.4%
	Mid-term contract	2.7%	2.1%	4.3%
	Long-term contract	14.3%	2.1%	9.9%
Inconsistency		8%	0%	2%

The combined result reflects a balanced approach, prioritizing Supply Sustainability, while acknowledging the importance of Quality, Supplier Reliability, Price, and Contract Strategy. Supply Sustainability (29.5%) emerges as the most critical factor, highlighting the plant's commitment to responsible sourcing and long-term coal availability. Coal Stock (25.8%) within Sustainability emphasizes maintaining adequate coal reserves while minimizing stockout risks. Contract Strategy (20.7%), Supplier Reliability (20%) and Quality (19.7%) are another key consideration, ensuring consistent, timely coal deliveries and meet the boiler system qualification. It represents the weight of Supply Realization (12.8%), Caloric Value (10%) and Long-Term Contract (9.9%) to ensure that the sustainability of supply is really fulfilled quantitively and qualitatively. The secondary considerations come up from Ordering Strategy (6.6%) which emphasizes efficient stock management practices through techniques like Just-in-Time and Economic Order Quantity. Delivery Time (5.3%) within the category of Supplier Reliability, and Price (3.5%), while not the top priorities, still plays a role.

Overall, the combined analysis portrays a decision-making process that prioritizes:

1. **Sustainable Sourcing:** Responsible coal mining practices and ensuring long-term coal availability.
2. **Reliable Supply:** Consistent and timely coal deliveries to avoid disruptions at the power plant.
3. **Fuel Efficiency:** Considering coal quality factors like caloric value to optimize plant operations.

By prioritizing these aspects, the PLTU Pelabuhan Ratu aims to achieve a balance between environmental responsibility, operational efficiency, and cost-effectiveness in coal supplier selection. The ranking of these criteria indicates the most important aspects in decision making. By evaluating suppliers against these weighted criteria, the AHP identifies the ones that best align with the plant's priorities.

Table IV.2 shows the ranking of alternative coal suppliers (18 suppliers, company A-R) for the PLTU Pelabuhan Ratu based on their priorities. Supplier A (13.9%) emerges as the top contender in the ideal mode. This indicates that under a scenario where all criteria in the AHP analysis have the highest possible importance, Supplier A aligns best with the PLTU Pelabuhan Ratu's priorities. Suppliers B (10.6%) and C (9.6%) follow closely, suggesting they are also strong options. Suppliers D to I (7.0% - 5%) are considerable suppliers to complement the overall plant's priorities. Suppliers J to R (<5%) have progressively lower priorities, indicating a potentially weaker fit with the plant's ideal criteria preferences.

The AHP results provide valuable insights into the relative importance of various factors considered during coal supplier selection at the PLTU Pelabuhan Ratu. This allows decision-makers to prioritize factors most critical for efficient energy management and plant performance within the Indonesian context. The supplier ranking derived from AHP offers a preliminary selection guide.

TABLE **ERREUR ! IL N'Y A PAS DE TEXTE REPONDANT A CE STYLE DANS CE DOCUMENT.**.2 SUPPLIER SELECTION RANK LIST USING ANALYTICAL HIERARCHY PROCESS (AHP)

Rank	***Alternative Suppliers***	***Priorities***
1	Supplier A	13.9%
2	Supplier B	10.6%
3	Supplier C	9.6%
4	Supplier D	7.0%
5	Supplier E	6.9%
6	Supplier F	6.3%
7	Supplier G	6.2%
8	Supplier H	5.4%
9	Supplier I	5.3%
10	Supplier J	4.3%
11	Supplier K	3.7%
12	Supplier L	3.6%
13	Supplier M	3.2%
14	Supplier N	3.0%
15	Supplier O	2.9%
16	Supplier P	2.9%
17	Supplier Q	2.7%
18	Supplier R	2.6%

TABEL **ERREUR ! IL N'Y A PAS DE TEXTE REPONDANT A CE STYLE DANS CE DOCUMENT.**.3 NUMBER OF SUPPLY REALIZATION IN PLTU PELABUHAN RATU IN 2020-2023

Month	**Coal Supply Realization (Metric Ton)**			
	2020	***2021***	***2022***	***2023***
January	337,455.706	297,948.340	322,027.696	356,433.655
February	346,255.621	259,802.449	387,794.104	360,026.984
March	421,008.235	319,728.104	327,342.499	375,256.898
April	389,768.380	274,151.738	395,716.617	378,951.939
May	272,589.705	325,920.451	312,141.784	344,053.944
June	397,350.502	294,428.849	364,185.906	379,888.220
July	296,927.216	273,780.288	250,417.086	225,867.866

Month	Coal Supply Realization (Metric Ton)			
	2020	*2021*	*2022*	*2023*
August	395,110.647	245,319.744	295,825.161	338,470.198
September	338,201.976	356,755.948	220,114.549	384,276.131
October	387,120.279	390,234.463	329,938.109	370,672.761
November	438,156.592	314,153.711	324,060.926	405,274.065
December	284,490.866	370,994.459	359,105.459	396,621.901
Total	4,304,435.725	3,723,218.544	3,888,669.896	4,315,794.562

4.2. MCS Results and Demand Prediction

The Monte Carlo Simulation (MCS) focused on predicting future coal demand at the PLTU Pelabuhan Ratu. By simulating random variations in historical demand data, the MCS generated a range of possible future demand values. Historical data of coal realization from suppliers in PLTU Pelabuhan Ratu are presented in Tabel IV.3.

The table presents historical coal demand data from January 2020 to December 2023, with monthly and annual totals. Coal demand appears to exhibit seasonal fluctuations. Generally, demand is higher during the dry season (April-October). This could be due to factors like increased agricultural irrigation needs, leading to higher electricity consumption for pumping water, besides air conditioner for buildings. While the overall demand seems to be increasing from 2020 to 2023 (4.3 million tons in 2020 vs. 4.32 million tons in 2023), there are significant variations between years. This could be influenced by various factors like changes in industrial activity, weather patterns, or energy policies. Some months show unusually high or low demand compared to their typical seasonal patterns. For example, July 2023 has a significantly lower demand than usual. Significant decrease of demand number influenced by lower supply realization and give impact to load percentage in consumption and electricity production (see Fig.1).

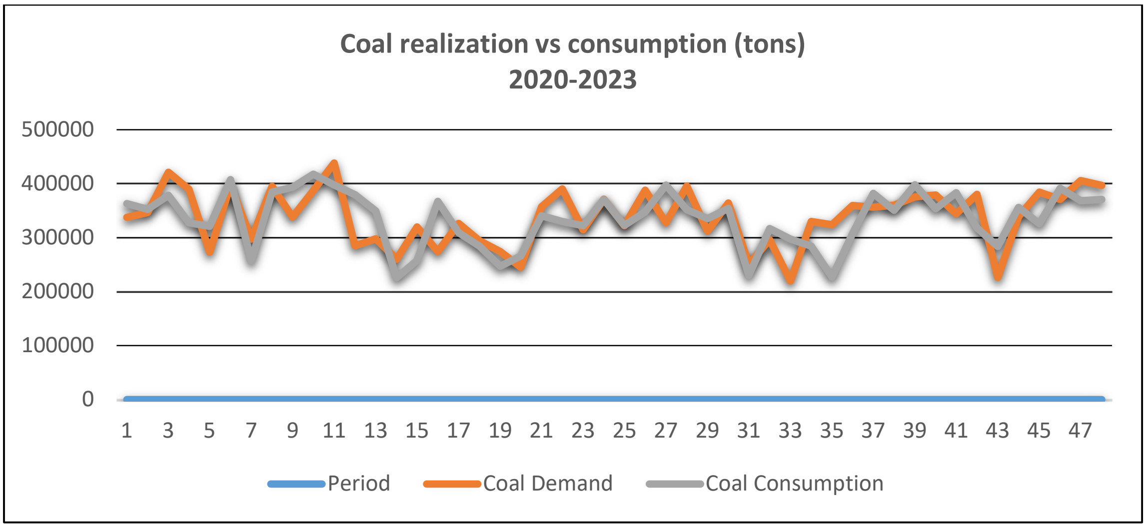

Fig. 1 Realization and consumption of coals in PLTU Pelabuhan Ratu 2020-2023

Fig.1 shows that coal consumption is strongly connected to the number of received supply. While, coal consumption is directly determining the energy generation. Thus, it is very likely that the data indicates that PLTU Pelabuhan Ratu is not reaching its maximum electricity production capacity due to limited supply of coal. This is in a good agreement with AHP result above that sustainability sourcing and reliable supply become the most important issues in PLTU Pelabuhan Ratu.

Based on statistical analysis, Fig.2 shows that supply realization in PLTU Pelabuhan Ratu has minimum extreme data distribution pattern. The data points in Fig.2 are clustered towards the lower end of the range. This means more frequent occurrences of lower supply realization values compared to higher ones. The tail on the right side (representing higher supply realization) is shorter or nonexistent compared to the tail on the left side (representing lower supply realization).

The data analysis suggests that most of the time, the amount of coal received (supply realization) is lower than what was planned or contracted for. This indicates a tendency for under-deliveries from the suppliers. This data distribution pattern has some potential implications:

- Under-deliveries can create uncertainty and potentially disrupt power generation schedules at the PLTU Pelabuhan Ratu.
- If the planned supply consistently exceeds actual needs, it might indicate inefficient procurement planning.
- Under-deliveries might require adjustments to power generation plans or emergency purchases, potentially impacting costs.

To handle this situation, either it is through reviewing the existing contracts, negotiating with suppliers, or exploring alternative sourcing options, the AHP model has considered these criteria. Hence, we believe that the alternative suppliers ranking could meet with many possible strategies. To implement the optimal strategies, demand forecasting model should be refined.

Based on the data distribution fit, the demand forecasting data model is shown in fig.3. Its highest accuracy is in about 338,000 – 342,000 tons/month range of supply in average needed, according to MAPE (mean absolute percentage error) < 10% [33]. The number of trials is 10,000 iterations with the level of confidence is 95%. The fluctuation probability seems still observed, with high variabilities. To prevent the impact of under supply, CFPP should assure that the suppliers comply their contract.

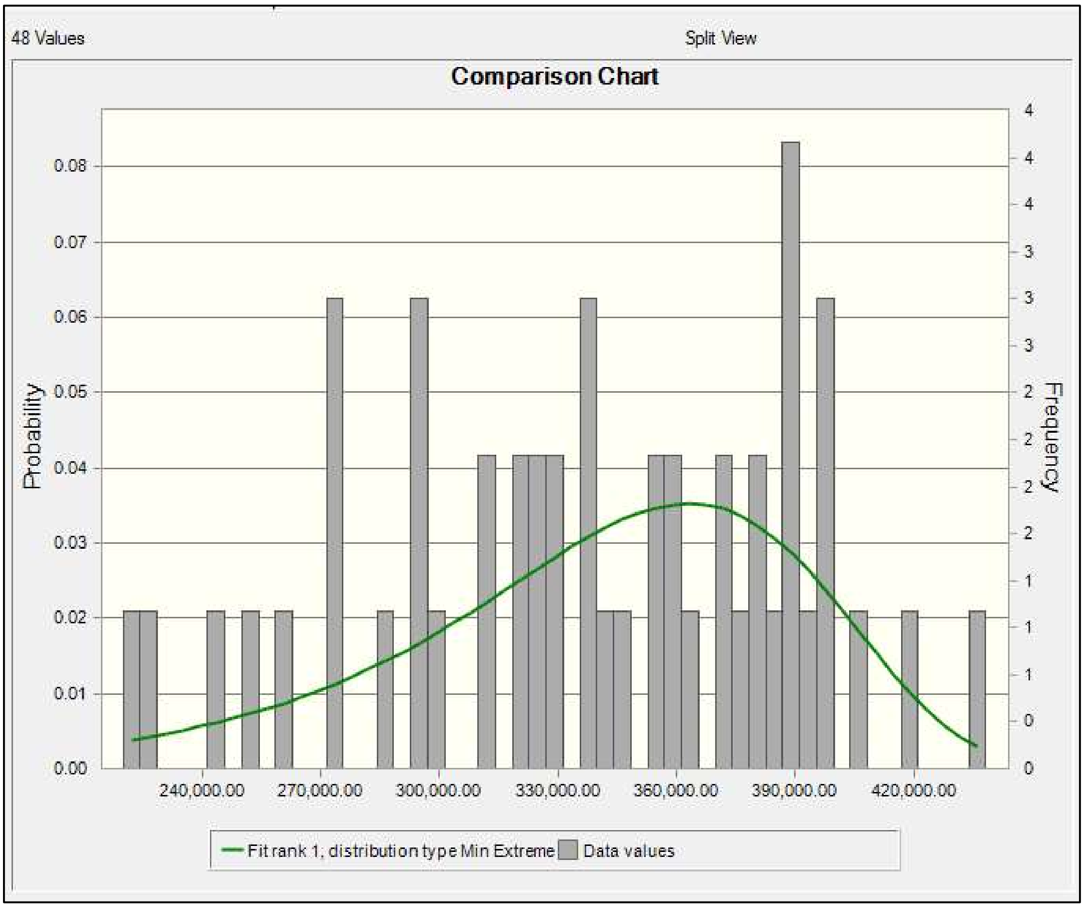

Fig. 2 Distribution data fit analysis of supply realization

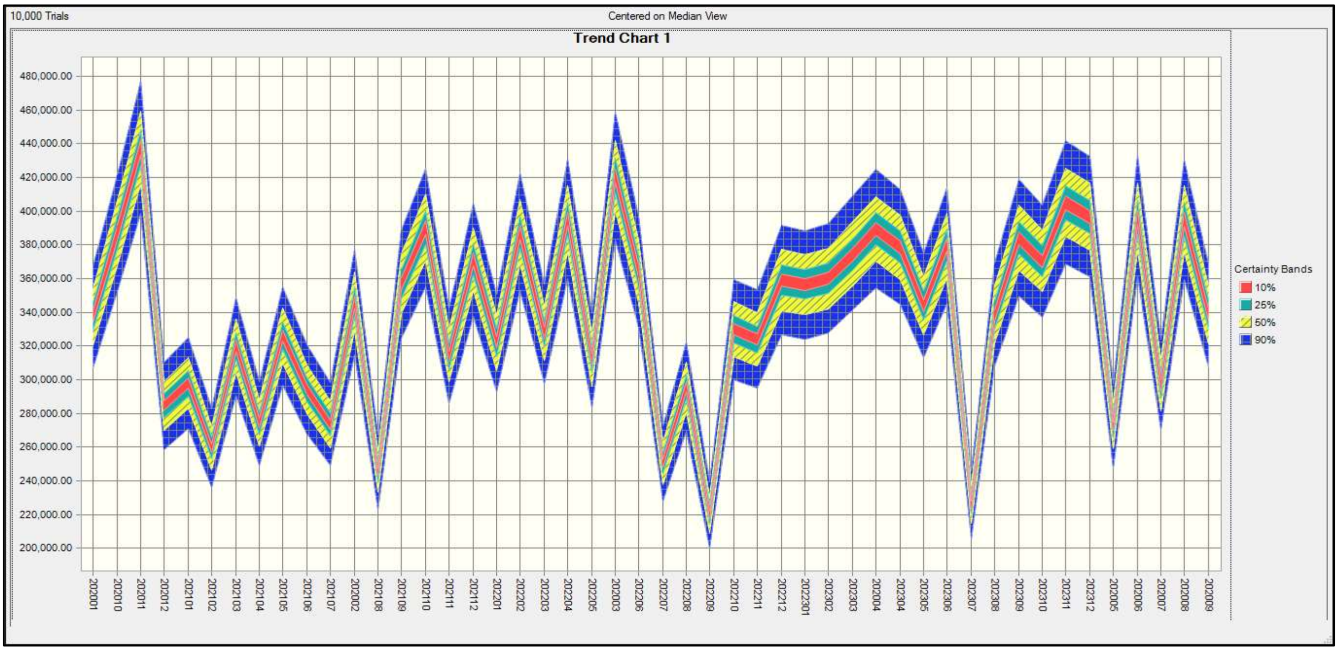

Fig. 3 Demand forecasting model based on median centered

To mitigate risks associated with under supply scenarios, historical data of suppliers' performance is presented in Table IV.3. based on the ASTM D388, most of suppliers supply low rank coal (<4800 kcal/kg). Even the contracted suppliers deliver the lower rank quality supply frequently. Their mean values indicate this asumption. The monthly supply also suggests that mean values are very close to the minimum values rather than the maximum. Thus, under supply is associated with poor performance of many suppliers.

TABLE **ERREUR ! IL N'Y A PAS DE TEXTE REPONDANT A CE STYLE DANS CE DOCUMENT.**.3 SUPPLIER HISTORICAL PERFORMANCE OF SUPPLY REALIZATION

No.	***Suppliers***	***Monthly Supply (ton)***			***Caloric value (kcal/kg)***		
		Min	***Mean***	***Max***	***Min***	***Mean***	***Max***
1	Supplier A	13,849.12	145,452.74	239,216.39	4,500.00	4,697.51	4,932.00
2	Supplier B	3,435.39	14,903.73	44,677.65	4,000.00	4,679.80	4,900.00
3	Supplier C	11,093.27	26,259.57	59,270.12	4,000.00	4,271.74	4,300.00
4	Supplier D	5,318.47	39,106.99	91,601.50	4,500.00	4,693.10	4,900.00
5	Supplier E	4,297.75	10,335.65	19,716.25	4,300.00	4,533.56	4,600.00
6	Supplier F	9,500.00	24,845.68	50,000.00	4,600.00	4,734.39	5,000.00
7	Supplier G	7,500.00	18,470.57	40,000.00	4,337.00	4,468.50	4,600.00
8	Supplier H	7,500.00	30,177.48	83,578.80	3,600.00	3,832.59	4,000.00
9	Supplier I	7,500.00	23,021.19	46,998.32	4,000.00	4,224.90	4,500.00
10	Supplier J	6,618.86	19,570.95	44,596.22	4,300.00	4,472.62	4,600.00
11	Supplier K	8,500.00	18,227.34	25,269.84	3,900.00	4,053.05	4,200.00

No.	*Suppliers*	*Monthly Supply (ton)*			*Caloric value (kcal/kg)*		
		Min	*Mean*	*Max*	*Min*	*Mean*	*Max*
12	Supplier L	7,740.71	16,903.41	35,402.92	4,000.00	4,105.00	4,200.00
13	Supplier M	7,500.00	16,548.43	35,000.00	3,600.00	4,105.18	4,150.00
14	Supplier N	7,454.47	8,129.10	8,763.09	4,089.00	4,360.50	4,632.00
15	Supplier O	7,320.44	13,639.75	54,500.00	3,750.00	4,026.82	4,100.00
16	Supplier P	7,203.60	9,655.06	25,661.82	3,949.00	4,106.90	4,200.00
17	Supplier Q	7,524.60	8,798.51	10,005.90	3,600.00	3,801.90	4,200.00
18	Supplier R	7,460.48	11,522.09	15,583.70	4,000.00	4,069.70	4,200.00

Prediction result for 36 coming months is presented in Table IV.4. As the comparative simulation, routine forecasting using Log-Hub is also conducted. The reliability of MCS forecasting is up to month-76 of the model in Single Moving Average mode (which best error level according to the software analysis). According to MCS, the forecasted mean value is 338,579.18 ton/month. Whereas, the routine simulation predicts that average value of monthly demand is 316,873.74 ton, lower than MCS that consider the probability. From the predictions result, the lowest demand is estimated about 253,424.95 ton by September, while the highest is predicted in January as 367,431.85 ton. Both numbers are within the range of predicted MCS.

TABLE **ERREUR ! IL N'Y A PAS DE TEXTE REPONDANT A CE STYLE DANS CE DOCUMENT.**.4 FORECASTING RESULT OF MONTE CARLO SIMULATION (MCS) AND LOG-HUB

Period	***Lower: 2.5%***	***Forecast***	***Upper: 97.5%***	***Log-Hub***
49	242,420.29	338.579.18	434,738.06	367,431.85
50	239,481.62	338.579.18	437,676.73	293,020.10
51	237,358.51	338.579.18	439,799.84	364,831.02
52	235,808.64	338.579.18	441,349.71	330,212.16
53	235,708.05	338.579.18	441,450.31	338,233.28
54	234,474.46	338.579.18	442,683.90	286,087.76
55	234,747.49	338.579.18	442,410.87	309,361.49
56	232,645.69	338.579.18	444,512.67	325,457.22
57	232,306.83	338.579.18	444,851.53	253,424.95
58	229,900.22	338.579.18	447,258.13	271,284.87
59	225,805.01	338.579.18	451,353.34	322,148.73
60	229,244.59	338.579.18	447,913.76	340,991.40
61	224,700.73	338.579.18	452,457.63	
62	234.889.89	338,579.18	442.268.47	
63	232,498.03	338.579.18	444,660.32	
64	230,469.60	338,579.18	446.688.75	

Period	*Lower: 2.5%*	*Forecast*	*Upper: 97.5%*	*Log-Hub*
65	230,765.15	338.579.18	446,393.20	
66	229,583.95	338,579.18	447.574.40	
67	226,925.60	338.579.18	450,232.75	
68	225,145.12	338,579.18	452,013.24	
69	219,492.74	338.579.18	457,665.62	
70	212,192.24	338,579.18	464,966.11	
71	209,352.78	338.579.18	467,805.58	
72	230,180.69	338,579.18	446,977.67	
73	220,323.81	338.579.18	456,834.54	
74	218,379.72	338,579.18	458,778.63	
75	199,710.03	338.579.18	477,448.33	
76	207,563.46	338,579.18	469,594.89	
77	---	338,579.18	---	
78	---	338.579.18	---	
79	---	338,579.18	---	
80	---	338.579.18	---	
81	---	338,579.18	---	
82	---	338.579.18	---	

4.3. Integration of AHP, MCS, and I/O Energy Conversion Analysis

Table IV.5 presents the simulation of demand planning, electricity production and logistic costs with integrated AHP, MCS and I/O energy conversion analysis approaches. All assumptions and calculation methods are mentioned in the methodology.

TABLE **ERREUR ! IL N'Y A PAS DE TEXTE REPONDANT A CE STYLE DANS CE DOCUMENT.**.5 SIMULATION OF DEMAND PLANNING, PRODUCTION OF ELECTRICITY ESTIMATION, AND LOGISTIC COSTS

No	*Operational Variabel*	*Scenario I*	*Scenario 2*	*Scenario 3*	*Scenario 4*	*Scenario 5*	*Scenario 6*
1	Heat rate (kcal/kWh)	2,754.827	2,754.827	2,754.827	2,754.827	2,754.827	2,754.827
2	Cut-off of supply (ton/month)	338,579.18	338,579.18	338,579.18	353,954.06	432,610.513	316,873.74
3	Supply planning (ton/month)	338,579,180.00	370,371,892.00	435,247,640.00	370,371,890.00	435,247,640.00	316,873,736.05
4	Weighted caloric	4,535.19	4,509.17	4,451.30	4,549.62	4,559.07	4,551.75

No	*Operational Variabel*	*Scenario I*	*Scenario 2*	*Scenario 3*	*Scenario 4*	*Scenario 5*	*Scenario 6*
	value (kcal/kg)						
5	Electricity production/month (kWh)	557,393,314.95	606,234,518.83	703,281,224.60	611,672,933.72	720,308,451.61	523,565,046.28
6	Electricity production/hour (kW)	761,466.28	828,189.23	960,766.70	835,618.76	984,027.94	715,252.80
7	Production capacity (%)	72.52%	78.88%	91.50%	79.58%	93.72%	68.12%
8	Logistic cost - CIF (Rp million)	331,575.13	363,984.75	421,210.82	364,267.23	427,091.89	312,044.50
9	Logistic cost - average (Rp/kg)	979.31	982.75	967.75	983.52	981.26	984.76
10	Operational cost (Rp/kWh)	594.87	600.40	598.92	595.53	592.93	596.00

Following are descriptions of the operational variables used in the calculations:

- Heat Rate: This refers to the amount of heat energy required to generate one unit of electricity (kWh) and is expressed in kcal/kWh. Here, it remains constant across all scenarios.
- Cut-off of Supply: This indicates the minimum amount of coal required per month (in tons) to avoid stock depletion. It varies across scenarios.
- Supply Planning: This represents the planned amount of coal to be supplied per month (in tons). It varies across scenarios.
- Weighted Caloric Value: This reflects the average calorific value of the coal used during the scenario (in kcal/kg). It varies slightly across scenarios.
- Electricity Production (Monthly & Hourly): These columns show the total electricity produced per month (kWh) and per hour (kW) based on the other variables. As expected, these values increase with higher planned supply.
- Production Capacity (%): This indicates the percentage of the plant's maximum capacity utilized in each scenario. It's calculated based on the electricity produced compared to a potential maximum.
- Logistic Cost (CIF & Average): These columns represent the costs associated with coal transportation and delivery. CIF (Cost, Insurance, and Freight) likely refers to the total landed cost, while the average cost is per kilogram of coal.
- Operational Cost (Rp/kWh): This is relative contribution to the final cost of generating electricity per unit (kWh), considering all factors like fuel cost, transportation, and potentially other operational expenses.

The table presents six different scenarios (Scenario 1 - 6) with varying values for the operational variables. Based on the assumption of a heat rate of 2754.83 kcal/kWh and a coal supply of 338,579.18 tons, the resulting electricity production can meet the power plant's production capacity requirements up to 72.52% (Scenario 1). According to the optimization point of the Monte Carlo simulation results for Scenarios 2-5, the optimal production capacity is within the operational range of 78-93%. The optimal calorific value range is between 4450-4550 kcal/kg. While, Scenario 6 as the minimum cut-off as well as demand planning, resulting 68.12% electricity generated of its maximum capacity.

AHP ranking is used to the shortlisted suppliers to meet the plant's criteria and coal demand based on MCS and other condition in the scenario planning. Average logistics costs are relatively equal across all scenarios, with the exception of Scenario 3 (Rp 967.75/kg) which evenly distributes supply requirements according to the mean delivery values of suppliers based on priority order (requirements met by 16 suppliers). Thus, the results of the supplier modeling using the AHP method are consistent with the results of the Monte Carlo simulation.

On the other hand, the logistics costs incurred in proportion to electricity productivity are observed to be most efficient in Scenario 5, amounting to Rp 592.93/kWh. In Scenario 5, the supply quantity follows the order of the AHP supplier model and can be met by 9 main suppliers. Thus, the results of AHP modeling and Monte Carlo simulation support each other.

However, Scenario 1 shows that the supply acceptance condition results in the second lowest average cost (after Scenario 3) and the second most efficient proportional operational cost (after Scenario 5) based on the number of suppliers (10 main suppliers) with highest supply probability. In addition, electricity production is relatively maintained at a capacity of 72.25%. Therefore, Scenario 1 is the most optimal result in an extreme minimum supply situation.

A comparison between Scenario 2 (11 suppliers) and 4 (9 suppliers), as well as 3 (16 suppliers) and 5 (9 suppliers), reveals that based on logistics costs, distributing coal demand according to the order and mean values of those suppliers results in a more cost-effective outcome compared to increasing the contract supply value with 10 main suppliers. This is because suppliers in the medium and lower priority groups can offer competitive and lower logistics costs. However, in terms of electricity production efficiency, it tends to be slightly lower compared to the results of blending the main suppliers. Thus, when coal demand increases but supply from main suppliers is limited, the trade-off between low logistics costs and electricity production efficiency can indeed be negotiated. The AHP supplier selection model can provide an alternative to meet production needs and good efficiency at competitive costs at the Pelabuhan Ratu Power Plant.

In Scenario 6, the simulation of coal demand allocation based on the supplier selection model results in electricity productivity of 523,565.05 thousand kWh per month or approximately 68.12% of the plant's maximum capacity. Average logistics costs are the most expensive of all scenarios (Rp 984.76/kg). The contribution of the cost per kWh of Scenario 6 to the operational cost (Rp 596.00/kWh) is also greater than Scenario 1 (Rp 594.87/kWh). Thus, Scenario 6 is relatively uneconomical compared to Scenario 1. In addition, electricity productivity in Scenario 6 is lower than in Scenario 1. Therefore, from the perspective of electricity production sustainability, Scenario 1 has the potential to maintain the electricity supply by 4.40% per month compared to Scenario 6, which does not consider supply probability.

Based on the simulation calculations in Table IV.5 above, it can be concluded that under extreme supply conditions, the most optimal monthly supply value is 338,58 thousand tons of coal, which supports the operation of the power plant unit up to 72.52% per month of the maximum capacity. The supply plan can be met by 10 suppliers according to the AHP model order, with alternative suppliers according to the portion of logistics cost considerations or electricity production efficiency. To improve production efficiency, the supply quantity option can be focused on the 9 main suppliers with a trade-off in increased logistics costs.

This study acknowledges limitations, such as the simplified I/O analysis might not capture the full impact of coal property variations. Future research can explore incorporating real-time data and more advanced I/O efficiency models for further refinement.

V. Conclusions

Based on the analysis of various scenarios and the Monte Carlo simulation results, this study identified key strategies for optimizing coal supply for the power plant under different conditions:

1. When coal supply is extremely limited, prioritizing the top 10 suppliers ranked by the AHP model with a monthly supply of 338,58 thousand tons can maintain power plant operation at up to 72.52% of its maximum capacity. Alternative suppliers can be considered based on logistics costs or efficiency needs.

2. Scenarios 2-5 highlight the potential for achieving a balance between cost and efficiency. By focusing on a production capacity range of 78-93% and utilizing coal with a calorific value between 4450-4550 kcal/kg, the power plant can operate more efficiently while keeping costs under control.
3. The analysis emphasizes the trade-off between logistics costs and electricity production efficiency. While focusing on the 9 main suppliers may improve efficiency, it might also increase logistics costs. Selecting suppliers based on a combination of factors like cost, efficiency, and supply probability can help achieve an optimal balance.
4. The consistency between the AHP supplier model results and the Monte Carlo simulation findings validates the effectiveness of the AHP approach for identifying optimal supplier selection strategies.

Overall, this study demonstrates the importance of using a data-driven approach to optimize coal supply for power plants. By considering factors like heat rate, coal properties, logistics costs, and production efficiency, decision-makers can choose the most appropriate supply strategy for different operating conditions.

Further research could explore integrating real-time data on coal prices, transportation disruptions, and electricity demand fluctuations into the optimization model for even more dynamic and adaptable supply strategies.

REFERENCES

[1] ESDM. (2022). Capaian kinerja sektor ESDM tahun 2021 dan rencana 2022. https://www.esdm.go.id/assets/media/content/content-capaian-kinerja-sektor-esdm-tahun-2021-dan-rencana-tahun-2022.pdf

[2] BP. (2022). BP Statistical Review of World Energy 2022.

[3] IEA. (2019). Coal 2019. IEA.

[4] IEA. (2023). Coal 2023 - Analysis and forecast to 2026. IEA.

[5] Perda Prov Jabar No. 2/2019 Tentang Rencana Umum Energi Daerah Provinsi Jawa Barat 2018-2050 (2019).

[6] Bappenas. (2023, August 1). Perkembangan Ekonomi Indonesia dan Dunia. Triwulan II, Edisi Vol. 7, No. 1 Agustus 2023.

[7] Kurniawan, R., Trencher, G. P., Edianto, A. S., Setiawan, I. E., & Matsubae, K. (2020). Understanding the multi-faceted drivers of increasing coal consumption in Indonesia. *Energies*, *13*(14), 3660..

[8] Hendra, W., & Mangkusubroto, K. (2022). The Stumbling Block of Net Profit Margin: A Case Study of PT PLN batu bara. Vol. 8 No. 2 (2022): JABM Vol. 8 No. 2, Mei 2022

[9] Noh, J., & Hwang, S. J. (2023). Optimization Model for the Energy Supply Chain Management Problem of Supplier Selection in Emergency Procurement. Systems, 11(1).

[10] Naderi, R., Nikabadi, M. S., Alem-Tabriz, A., & Pishvaee, M. S. (2020). Supply Chain Network Design Integrating Economic, Risk and Energy Sustainability. Environmental Energy and Economic Research, 4(4), 321–332.

[11] Subramanian, N., & Ramanathan, R. (2012). A review of applications of Analytic Hierarchy Process in operations management. International Journal of Production Economics, 138(2), 215–241.

[12] Battesini, M., & Koppe, J. C. (2024). Coal-fired electricity generation in Brazil under public regulation: security-of-supply assessment. International Journal of Energy Sector Management, 18(2), 390-410.

[13] Gedik, R., Medal, H., Rainwater, C., Pohl, E. A., & Mason, S. J. (2014). Vulnerability assessment and re-routing of freight trains under disruptions: A coal supply chain network application. Transportation Research Part E: Logistics and Transportation Review, 71, 45-57.

[14] Perera, A. T. D., Nik, V. M., & Scartezzini, J. L. (2019). Impacts of extreme climate conditions due to climate change on the energy system design and operation. Energy Procedia, 159, 358-363.

[15] Jain, R., Reindorp, M., & Chockalingam, A. (2023). Buyer-backed purchase-order financing for SME supplier with uncertain yield. European Journal of Operational Research, 307(2).

[16] Johnson, P., Howell, S., & Duck, P. (2017). Partial differential equation methods for stochastic dynamic optimization: an application to wind power generation with energy storage. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 375(2100), 20160301.

[17] Banchuen, P., Sadler, I., & Shee, H. (2017). Supply chain collaboration aligns order-winning strategy with business outcomes. IIMB Management Review, 29(2), 109–121. https://doi.org/10.1016/j.iimb.2017.05.001

[18] Yang, S., & Wang, R. (2013). Research on Power Coal Supplier Selection Based on AHP and Fuzzy Comprehensive Evaluation Method.

[19] Habibah, N., & Kusumastuti, R. D. (2020). Determining Criteria for Supplier Selection in the Indonesian Oil and Gas Industry. The South East Asian Journal of Management, 14(2), 215–229.

[20] Siregar, M. L., & Suparno, S. (2021). Selecting The Best Supplier in Procurement Section (Goods Spot Purchase) - Departement SCM With Analytical Hierarchy Process (AHP) Method. *IPTEK Journal of Proceedings Series*, *0*(6), 504. https://doi.org/10.12962/j23546026.y2020i6.11151

[21] Yu, Z., Li, Z., & Ma, L. (2023). Strategies for the Resilience of Power-Coal Supply Chains in Low-Carbon Energy Transition: A System Dynamics Model and Scenario Analysis of China up to 2060. *Sustainability (Switzerland)*, *15*(9).

[22] Moghaddam, K. S. (2015). Supplier selection and order allocation in closed-loop supply chain systems using hybrid Monte Carlo simulation and goal programming. *International Journal of Production Research*, *53*(20), 6320–6338. https://doi.org/10.1080/00207543.2015.1054452

[23] Petrova, T. v., & Strekalov, S. v. (2019). A competitive mechanism for selecting a supplier by a coal mining company based on the use of a system for monitoring the exploitation of material and technical resources. *IOP Conference Series: Earth and Environmental Science*, *377*(1). https://doi.org/10.1088/1755-1315/377/1/012061

[24] Naderi, R., Nikabadi, M. S., Alem-Tabriz, A., & Pishvaee, M. S. (2020). Supply Chain Network Design Integrating Economic, Risk and Energy Sustainability. *Environmental Energy and Economic Research*, *4*(4), 321–332. https://doi.org/10.22097/eeer.2020.239168.1163

[25] Wibowo, A. B., & Pujawan, I. N. (2018). Procurement strategy and supply risk analysis of coal by considering price fluctuation and supplier delivery time. *Proceeding of the International Conference on Industrial Engineering and Operations Management*, 2903–2913. https://scholar.its.ac.id/en/publications/procurement-strategy-and-supply-risk-analysis-of-coal-by-consider

[26] Wu, T.-Y., Shieh, S.-S., Jang, S.-S., & Liu, C. C. L. (2005). Optimal Energy Management Integration for a Petrochemical Plant Under Considerations of Uncertain Power Supplies. *IEEE TRANSACTIONS ON POWER SYSTEMS*, *20*(3). https://doi.org/10.1109/TPWRS.2005.852063

[27] Yucekaya, A. (2013). Cost Minimizing Coal Logistics for Power Plants Considering Transportation Constraints. *International Journal of Smart Grid and Clean Energy*, *2*. http://www.jtle.net/uploadfile/2013/0903/20130903023513623.pdf

[28] Sajid, Z., & Javaid, A. (2018). A Stochastic Approach to Energy Policy and Management: A Case Study of the Pakistan Energy Crisis. https://doi.org/10.3390/en11092424

[29] Maitra, S., Mishra, V., & Kundu, S. (2023). A Novel Approach with Monte-Carlo Simulation and Hybrid Optimization Approach for Inventory Management with Stochastic Demand. *ArXiv*, *abs/2310.01079*.

[30] Abud, T. P., Augusto, A. A., Fortes, M. Z., Maciel, R. S., & Borba, B. S. M. C. (2023). State of the Art Monte Carlo Method Applied to Power System Analysis with Distributed Generation. In *Energies* (Vol. 16, Issue 1). MDPI. https://doi.org/10.3390/en16010394

[31] Saaty, R. W. (1987). THE ANALYTIC HIERARCHY PROCESS-WHAT IT IS AND HOW IT IS USED. 9(5), 161–176.

[32] Guevara, Z., Rodrigues, J., & Domingos, T. (2015). The ultimate energy input-output model. In *23rd International Input Output Conference in Mexico City. México, DF Disponible en: https://www. iioa. org/conferences/23rd/papers/files/2029_20150423041_TheultimateEIOmodel. pdf. Consultado* (Vol. 24, No. 01, p. 2019).

[33] Moreno, J. J. M., Pol, A. P., Abad, A. S., & Blasco, B. C. (2013). Using the R-MAPE index as a resistant measure of forecast accuracy. Psicothema, 25(4), 500-506.